ACTUATION OF ATOMIC FORCE MICROSCOPE CANTILEVERS IN FLUIDS USING ACOUSTIC RADIATION PRESSURE

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Abstract – Actuation of microcantilevers in fluids has applications such as atomic force microscopy, fluid mixing and mechanical property characterization in microchannels. In this paper of a microfluidic actuator, which utilizes acoustic radiation pressure (ARP) to exert DC and AC forces on a microcantilever is discussed. An atomic force microscope (AFM) cantilever has been used to demonstrate the capabilities of this actuator. The method allows the application of a localized force at a desired location on a cantilever with a 5MHz bandwidth. The localized nature of the applied force allows the characterization of flexural and torsional oscillation modes of the AFM cantilevers. Tapping mode atomic force microscopy was also carried out using the ARP actuator.

I. INTRODUCTION

Among the numerous applications of microcantilevers there are several of them which benefit from active actuation of the microcantilever. It has been shown that mixing in a microchannel or characterization of the mechanical properties of a fluid can be achieved by vibrating a microcantilevers by means of an external force [1]. Many atomic force microscopy imaging modalities, such as tapping mode imaging of biological samples, also require the actuation of microcantilevers in liquids. Various methods, which utilize piezoelectric actuators, magnetic interactions and electrical interactions, have been used to vibrate AFM cantilevers in liquids. The first and the most common method is using either the z-piezo of the AFM system or a piezoelectric actuator attached to the cantilever holder [2]. This methods effectively vibrate the whole aperture and resulting amplitude spectrum for the tip oscillation contains unwanted spurious mechanical resonances which are not related to the behavior of the AFM cantilever [3]. In order to solve this problem a number of methods, which use magnetic, electrostatic interactions or integrated piezoelectric actuators, has been proposed [4][5]. The methods that utilize magnetic interactions require either a magnetic coating or a magnetic particle on the AFM cantilever together with a solenoid to produce a magnetic field. Recently, acoustic radiation pressure generated by a focused acoustic transducer has been introduced as another actuation mechanism [7]. This method does not require any special cantilevers or large magnetic fields and it is very suitable for array fabrication. In this paper this ARP actuator is used for flexural and torsional resonant mode characterization of AFM cantilevers and tapping mode AFM imaging.

II. THEORY

When a propagating acoustic wave encounters an interface along on its path in an unconfined medium, it exerts a force on this interface, which is known as the Langevin acoustic radiation pressure. The magnitude of this pressure depends on the intensity of the incident acoustic wave and its propagation speed. The time averaged energy density incident on the interface, U, can be expressed as

$$U = \frac{p_i^2}{2\rho c}\left(1 + |\Gamma|^2\right)$$

(1)

where p_i, ρ, Γ and c represents the amplitude of the time harmonic acoustic wave, the density of the fluid, reflection coefficient of the acoustic wave and the speed of sound in the liquid medium, respectively. Similar to electromagnetic radiation pressure, the magnitude of the acoustic radiation pressure incident on the interface is given by the ratio of the incident energy density U to the speed of sound c. The $p_i^2/(2\rho c)$ term in Eq. 1 represents the intensity of the incident acoustic wave, which will be denoted by I_i. Combining these, the acoustic radiation pressure on the interface, Ω, is given by

$$\Omega = I_i \frac{\left(1 + |\Gamma|^2\right)}{c}$$

(2)

Note that the acoustic radiation pressure is much more efficient in generating forces as compared to optical radiation pressure because the speed of sound is several orders of magnitude smaller than the speed of light.

In this paper, a focused acoustic transducer, which was designed originally for ink printing applications, is used to exert acoustic radiation force on various AFM cantilevers [6]. This transducer, which will be referred as the ARP actuator, consists of an acoustic Fresnel lens micromachined on a glass substrate and a ZnO transducer deposited on the back of the same substrate. Assuming perfectly matched electrical and acoustic networks and a reflecting substrate the maximum force per input power that ARP actuator can produce is 1.33nN/µW. The theoretical limit on the beam width, d, at the focal spot is given by d=1.02λ which translates to ~9 µm for a frequency of 174MHz. More information on the device and the actual performance of the device can be found elsewhere [7].

III. EXPERIMENTAL SETUP AND RESULTS

The experimental setup shown in Fig. 1 consists of a commercial AFM system, AFM controller, computer, RF signal generator to drive the ARP actuator and a lock-in amplifier to record the amplitude and phase information in some experiments. AFM cantilever is mounted on a transparent holder and ARP actuator placed underneath the cantilever like a sample, whereas the actual sample was placed on the transducer substrate near the acoustic Fresnel lens. The RF amplifier was used to drive the transducer with a carrier frequency of 174 MHz. This RF signal was amplitude modulated with the desired frequency to apply time harmonic forces. The lock-in amplifier, which was synchronized with the AM modulation signal to the RF amplifier, is used to obtain the flexural mode profile data with high SNR.

Figure 1 – Schematic of the experimental setup used to perform tapping mode imaging and resonant mode characterization

Figure 2- Normalized amplitude of the frequency response of the ARP actuator

The frequency response of the transducer, shown in Fig. 2, is obtained as follows: The RF frequency of the input is varied in the 170-180MHz range while applying AM modulation at 200Hz. The deflection of the cantilever at 200Hz is measured by using a lock-in amplifier at the standard deflection output of the AFM system. The results show that the normalized response of the transducer stays within 6 dB of the maximum value over a 10MHz range. The dominant periodic variation in the frequency response is due to the resonant cavity behavior of the glass substrate.

In order to demonstrate the ability of exerting a DC force on the cantilever, the output of the RF generator was modulated with a step waveform. The input waveform to the transducer and the corresponding photodetector output indicating the cantilever deflection are shown in Figure 3. As expected, response of the cantilever is dominated by the first flexural resonant mode of the cantilever.

A unique property of the ARP actuator is its ability to generate point-like forces on the AFM cantilever. The localized nature of the applied force can be used to characterize the flexural and torsional modes of the cantilever by moving the focal spot position over the

Figure 3 –The square wave modulated RF signal applied to the ARP actuator and the resulting cantilever deflection signal from photodetector

cantilever and recording the oscillation amplitude and phase from the deflection signal while the sample is not placed on the transducer substrate. In the flexural mode characterization experiment 450 um long etched silicon probes were used. The resonant frequency in air and spring constant of the cantilever are given by the vendor as 6-20 kHz and 0.02-0.1N/m. Using the setup in Fig. 1, the AC excitation signal applied on the Z-piezo is directed to the AM modulation input of the RF signal generator, which is used to drive the ARP actuator. Then the tip of the cantilever is placed at the focal spot of the ARP actuator. Modulation frequency generated by the external signal generator was set to the desired resonant mode. The first three flexural resonant frequencies are found at 2.6, 19.7 and 56 kHz respectively. The cantilever is then moved along its length while recording the amplitude and phase information as a function of position. The amplitude of oscillation for the first flexural mode is given in Fig 2. In order to verify our results a very simple analytical model is constructed based on simplifying assumptions that the ideal, lossless modal shapes of the cantilever are unchanged and the incoming acoustic beam creates a Gaussian force profile on the cantilever. Figure 4 shows the prediction of this simple model fitted to the observed amplitude data. In these plots the free end of the cantilever is to the left of the graph. The ripple like variations seen in the experimental data is due to the reflections at the interface between the liquid and the cantilever which is tilted by 11° with respect to the glass substrate.

Torsional mode characterization is done in a similar fashion to the flexural mode characterization. For this purpose, the AFM cantilever is moved in a 100μm x 100μm area while recording the amplitude and phase of the cantilever motion as two separate "images". The cantilever motion is determined by monitoring the lateral difference signal from the quad-photodiode. A silicon nitride micromachined contact mode is used for these experiments. The length of this cantilever is 100μm whereas the spring constant of the cantilever is given by the vendor as 0.58 N/m. Figure 5.a. shows the amplitude
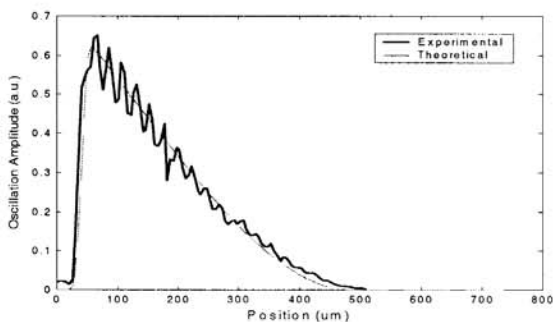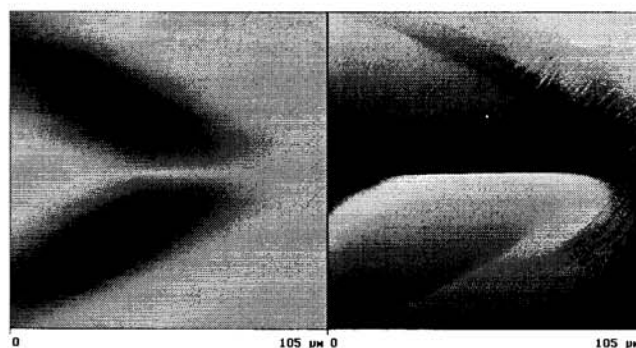

Figure 5 - The amplitude (a) and phase (b) "images" of the first torsional resonant mode of a V-shaped silicon nitride cantilever

and Fig 5.b. shows the phase of oscillation of the first torsional mode of the cantilever, which was found at 50kHz. Lighter colors on the amplitude image correspond to larger magnitude of oscillation. The difference between the dark and light areas in the phase image is 180° so that two sides of the cantilever are moving in opposite directions as expected.

In order to demonstrate tapping mode imaging with ARP actuator a sample is placed near the acoustic Fresnel lens as shown in Fig. 1. The thickness of the sample was selected to be 300μm because of the conditions imposed by the focal length of the Fresnel lens, and the geometry of the AFM cantilever. The sample consists of 100nm thick aluminum lines with 4μm pitch sputter deposited on a silicon substrate. First the cantilever is brought to the focal spot of the ARP actuator where it is also very close to touching the surface of the sample, then the cantilever is vibrated using the ARP actuator and it was engaged on the surface as in the regular tapping mode. During imaging, tapping mode vibration amplitude was 200 nm, which was obtained with an input RF signal power of 10dBm produced by the RF signal generator. For comparison, a standard contact mode image of the same region was obtained. Figures 6.a. and 6.b. show the images obtained with tapping mode with ARP and contact mode respectively.
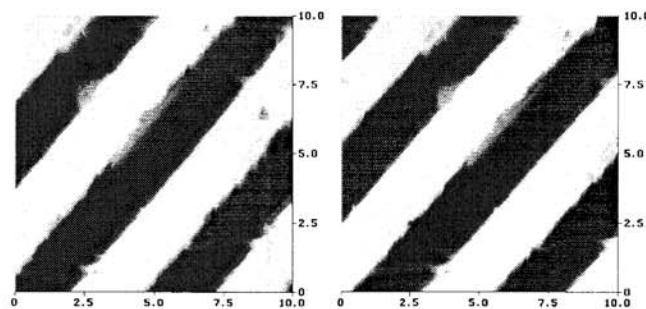

Figure 4 –Oscillation profile of the first flexural resonant mode

Figure 6- a) Tapping mode image with ARP actuator and b) standard contact mode images (10μm x 10μm) of an aluminum diffraction grating on silicon substrate.

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IV. CONCLUSION

It is shown that acoustic radiation pressure generated by thin piezoelectric films at RF frequencies can be used as a wideband (>5MHz) actuator, capable of applying point-like forces to the desired locations on a microcantilever. A commercial AFM system is modified to demonstrate the capabilities of the actuator on AFM cantilevers. Flexural and torsional resonant modes of various AFM cantilevers are characterized in wide frequency range. Tapping mode imaging in liquids was also carried out with very large vibration amplitude. These results suggest that the actuation scheme can be used for fluid characterization in fluidic channels based on remotely actuated cantilevers. It should also be noted that the ARP actuator is also very suitable for the excitation of an array of cantilevers since it does not rely on vibrating the whole liquid cavity of creating a large scale magnetic field, nor does it require any special coating.

V. ACKNOWLEDGEMENTS

VI. REFERENCES

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